The Effects of Ambient Ozone on Lung Function in Children: A Reanalysis of Six Summer Camp Studies

Patrick L. Kinney,[1] George D. Thurston,[2] and Mark Raizenne[3]

[1]Division of Environmental Sciences, Columbia University School of Public Health, New York, NY 10032 USA; [2]Institute of Environmental Medicine, New York University Medical Center, Long Meadow Road, Tuxedo, NY 10987 USA; [3]Health Canada, Ottawa, Ontario, Canada

Studies of children attending summer camps often have observed relationships between daily outdoor ozone (O_3) concentrations and decreased lung function that are qualitatively similar to results seen in human chamber studies. The former studies, focusing on the pulmonary effects of O_3 and associated pollutants on children under natural conditions of exposure, are potentially of great importance to understanding the public health impact of ambient O_3. However, a thorough assessment of the results of these studies has been hampered by differences in the analysis and reporting of data across the various studies. We obtained data sets from six summer camp studies carried out by three separate investigative groups, including two New Jersey studies performed by New York University, two studies in Ontario carried out by Health and Welfare Canada, and two studies in southern California. The data consisted of sequential, daily measurements of forced expiratory volume in 1 sec (FEV_1), peak expiratory flow rate (PEFR), and 1-hr O_3 concentration in the hour preceding lung function measurements for each child. We analyzed the relationships between lung function and O_3 using linear regression models that fit subject-specific intercepts and a single, pooled O_3 slope. These models were fit for each of the six studies separately and for all studies combined. All of the study-specific slopes of FEV_1 on O_3 were negative (i.e., increased O_3 associated with decreased FEV_1); five of six were statistically significant. Analysis of the combined six-study data set yielded a slope of -0.50 ml FEV_1/ppb O_3 ($p<0.0001$). Addition of time-trend variables to the combined-data analysis diminished, but did not eliminate, the FEV_1–O_3 relationship. Study-specific slopes for PEFR on O_3 were more variable. Combined over studies, no significant relationship was observed between PEFR and O_3. However, this negative finding appeared to be partially confounded by time trends in PEFR. The results of this reanalysis provide strong evidence that children exposed to O_3 under natural conditions experience decreases in FEV_1 of the kind demonstrated in laboratory studies, and raise concern that other acute respiratory effects observed in those studies (e.g., pulmonary inflammation) may also occur in young people exposed to ambient O_3. *Key words*: air pollution, children, epidemiology, lung/pulmonary function, ozone, summer camps. *Environ Health Perspect* 104:170–174 (1996)

Ozone (O_3) is a ubiquitous pollutant in outdoor air, frequently reaching 1-hr concentrations that exceed the National Ambient Air Quality Standard of 120 ppb. Because O_3 is formed through photochemical reactions involving nitrogen oxides and hydrocarbons, the highest and most broadly peaked O_3 concentration profiles often occur downwind of, rather than directly in, major source areas such as large cities.

Short-term exposures to ambient-level O_3 concentrations have been shown to result in a spectrum of effects on the human respiratory system, including drops in lung function (i.e., measures of lung volume and expiratory flow rates), increases in lung reactivity to other irritants, and pulmonary inflammation (*1–4*). The bulk of the data revealing these effects derive from chamber studies, which typically involve the study of relatively small numbers of healthy, white, adult, male volunteers exposed to pure O_3 under controlled laboratory conditions along with some form of exercise. While each individual chamber study has necessarily been limited in scope, the large number of chamber studies carried out in the past 20 years has yielded a rather extensive database for certain outcomes, most notably lung function. McDonnell and colleagues (*5*) accumulated data on 290 adult, white, male subjects from 5 separate chamber studies, with the goal of determining whether individual lung function response to O_3 is related to age, height, baseline lung function, allergen sensitivity, and other factors. Of these factors, only age had a consistent influence on responsiveness, with response diminishing with increasing age.

From the perspective of assessing the public health impact of O_3 exposures under real-world conditions, however, the chamber study database presents some limitations. First, the precisely controlled exposure conditions are unlike those that occur during many ambient episodes, where broad, multi-hour peaks, often accompanied by fine particulate matter, are observed. Second, relatively few chamber data are available on children and those with moderately severe lung disease, two population subgroups that may be at elevated risk of ozone-induced health impacts.

Epidemiologic studies have examined the acute pulmonary effects of ambient O_3 under natural conditions. These "field studies" can be categorized into three general types: summer camp studies, exercise studies, and daily life studies. All three designs involve collection of repeated measurements on individuals and analyze the association between lung function and day-to-day changes in O_3 concentrations, with each subject serving as his or her own control. In contrast to chamber studies, field studies examine the human health effects of O_3 under real-world conditions, with natural patterns of O_3 exposure and levels of co-pollutants and other environmental factors.

The most extensively and consistently used field study design for investigating acute O_3 effects has been the camp study, which involves collection of sequential (usually daily) lung function data on children attending summer camps, along with concurrent measurements of air pollution concentrations and meteorological conditions. Camp studies, involving sequential, usually daily, measurements of lung function and air pollution concentrations, offer the significant advantage that individual pollution exposures in a potentially large subject population can be easily and accurately estimated using a single, on-site monitoring station. In addition, these studies directly investigate associations of pulmonary function with natural diurnal patterns of O_3 and associated co-pollutants, which often involve prolonged daytime peaks. Finally, the focus is on children, whose lungs are still developing.

Address correspondence to P. L. Kinney, Division of Environmental Sciences, Columbia University School of Public Health, 60 Haven Avenue, B-1, New York, NY 10032 USA.

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Many camp studies have supported the conclusion that ambient O_3 exposures in active children are associated with short-term declines in population average lung function (*3,6*). Other studies have yielded negative or equivocal results (*7–10*). It is not clear to what extent these differences are merely due to variations in data analysis and reporting methods across studies and to what extent they may represent substantive differences in results. Concerns about potential confounding by other pollutants or weather variables, which may co-vary with O_3, have led some to question the attribution of the observed associations to O_3 per se. These uncertainties have limited the causal inferences that can be drawn from the camp studies and have limited their use in risk assessment and regulatory decision making.

Due to the common study design, data from camp studies are amenable to reanalysis. By pooling data from several studies, a more robust overall relationship between naturally occurring O_3 exposures and decreased lung function can be estimated. A collective analysis also can yield insights into differences across studies in the relationship between lung function and O_3, without the influence of differing analytical methods.

This article presents the results of our reanalysis of the original lung function and O_3 data from six recent summer camp studies. These studies include two in northwestern New Jersey (*3,11*), two in southern California (*6,9*), and two in Ontario (*8,12*). Using a consistent analytical method, results are reported on the relationship between lung function and O_3 for each individual study and for all studies combined.

Methods

The 1984 Fairview Lake, New Jersey, study was conducted by researchers from New York University and Harvard University during a 4-week period in July and August at a summer YMCA camp in northwestern New Jersey (*3*). Once per day, usually in the afternoon, lung function was measured on each of up to 91 children (53 males and 38 females, 8–15 years of age). The Fairview Lake study was repeated in 1988, this time with 46 campers (33 males and 13 females, 8–14 years of age) and with function measurements collected in both the morning and the late afternoon (*11*). This design allowed consideration of changes in function during the course of each day.

The Lake Couchiching study was conducted collaboratively by Health and Welfare Canada and Harvard University over 10 days in late June and early July of 1983 (*7,12*). Lung function data were collected twice daily (0730–0930 hr and 1630–1830 hr) for 52 campers (including 23 asthmatics: 12 males and 11 females, and 29 nonasthmatics: 16 males and 13 females), who ranged from 7 to 15 years of age. These researchers also conducted a follow-up study at a Girl Guide camp located beside Lake Erie in southern Ontario during 6 weeks in June, July, and August 1986 (*7,8*). In that study, referred to as "CARES," spirometry was performed daily on 112 female campers, who averaged 11.6 years of age.

Two summer camp studies were conducted in California with support from General Motors Corporation. The first took place at a church-sponsored summer camp in the San Bernardino Mountains (elevation 1740 m) (*6*). Over a 3-week period in June and July 1987, 43 children (19 males and 24 females, 7–13 years of age) performed spirometry up to three times per day. During late June through early August 1988, a follow-up study was conducted at Pine Springs Ranch, east of Los Angeles (*9,10*). Lung function testing was carried out twice daily on each of 295 campers (ages 8–17) who attended one of six separate, sequential, 1-week camps.

Working data sets for each study reviewed above were obtained either directly from members of the original study teams, or through third parties (see Acknowledgments). A common feature of all six data sets was the availability of afternoon spirometric lung function data collected over many days on many subjects, along with the previous 1-hr average O_3 concentrations. For consistency, the present analysis focused on afternoon lung function measurements. Except as noted, if more than one afternoon lung function measurement was available for a given subject on one day, only the last measurement was used in the analysis. Because too few asthmatic subjects were available to analyze as a separate group (only the Lake Couchiching study included asthmatics), asthmatics were excluded from these analyses.

In each of the original studies, lung function data were collected by spirometry using methods that conformed closely to guidelines published by the American Thoracic Society (*13*). The present analysis was limited to data on forced expiratory volume in 1 sec (FEV_1) and peak expiratory flow rate (PEFR). Ozone measurements were collected using automated real-time monitors (based on either UV photometry or chemiluminescence), with instrument checks and calibrations conducted at regular intervals.

Data were analyzed using analysis of covariance methods via the GLM procedure of the SAS system (SAS Institute, Cary, North Carolina). The analysis was performed using data on four variables from each study: subject ID, FEV_1, PEFR, and the 1-hr average O_3 concentration in the hour preceding the lung function measurements.

For each study, linear regression models were fit relating FEV_1 or PEFR (the dependent variables) to O_3 (the independent variable). Regression models included a single, pooled O_3 slope and separate intercepts for each subject (to account for differences in average lung function across subjects). After obtaining study-specific results, the combined six-study data set was used to estimate the mean slopes across all studies for FEV_1 or PEFR regressed on O_3. These analyses were repeated with the addition of linear or higher-order functions of test number in order to fit the time-trend in repeated lung function measurements noted in previous studies (*9,14,15*). Ambient temperature was not included as a covariate in the analysis because human chamber studies have shown that direct effects of temperature on lung function are minimal within the normal ambient range (*16*).

Results

Table 1 presents data summaries for the six studies. Tables 2 and 3 present slope estimates for FEV_1 and PEFR, respectively, for each of the six studies analyzed separately. Nearly all of the slopes were negative, indi-

Table 1. Key descriptive statistics for six studies of the lung function response of children to air pollution

Study	Total no. of subjects	Total no. of observations	Mean observations/ subject	Mean O_3 (ppb)[a]	Maximum O_3 (ppb)	Mean FEV_1 (l)	Mean PEFR (l/sec)
Fairview Lake, 1984	91	1237	13.6	53	113	2.14	4.36
Fairview Lake, 1988	46	577	12.5	69	137	2.39	NA
Lake Couchiching, 1983	29	244	8.4	59	95	2.41	5.48
CARES, 1986	112	1228	11.0	71	143	2.34	5.51
San Bernardino, 1987	43	255	5.9	123	245	2.06	5.07
Pine Springs, 1988	295	1826	6.2	94	161	2.19	4.52

Abbreviations: FEV_1, forced expiratory volume in 1 sec; PEFR, peak expiratory flow rate; NA, PEFR data not available for this study.
[a]1-hr average, at time of afternoon lung function measurement.

cating that higher concentrations of O_3 were consistently associated with decreased lung function. FEV_1 slopes spanned an approximate fourfold range (-0.2 to -1.3 ml/ppb). Five of the six slopes were statistically significant. Peak flow results (Table 3) were less consistent. Four of the five slopes were negative, two of which were statistically significant. The PEFR slope for the Pine Springs study was unique in being positive and statistically significant. Individual analysis (not shown) of the 6 separate weeks of the Pine Springs camp revealed that only week 6 had a statistically significant positive slope of PEFR on O_3. Over the 6 days of data collection during week 6, both PEFR and O_3 increased markedly, resulting in a strong positive, but likely spurious, correlation between these two variables. The increase in PEFR probably reflected the positive training effect that has been noted in previous studies. These results illustrate the potential for confounding of O_3 effects by time trends in repeated spirometry. Exclusion of week 6 from the analysis of Pine Springs data resulted in a slightly positive, but nonsignificant, overall slope for Pine Springs. There was no evidence that the overall results for the Pine Springs camp were unduly influenced by data from a subset of subjects with very narrow ranges in O_3 exposures.

The relationship between lung function and O_3 was analyzed for the combined, six-study data set (Table 4). The overall FEV_1 slope on O_3 was -0.50 ml/ppb (SE = 0.07; p = 0.0001). The overall PEFR slope was positive but non-significant. This PEFR result was heavily influenced by data from the Pine Springs camp, which, as noted earlier, had a positive slope and had the largest number of subjects (295) and observations (1826). When data from this one study were set aside, the PEFR slope was -0.99 ml/sec/ppb (SE = 0.33; p = 0.003).

Exploratory analysis of the time trend in FEV_1 (independent of O_3) showed that FEV_1 tended to drop over the first four to five measurements, followed by a gradual increase and leveling off (results not shown). This trend was well fit by a third-order polynomial (i.e., linear, squared, and cubed trend variables were all statistically significant in a multiple regression analysis). The temporal pattern for PEFR was adequately fit by a simple linear increase over time. The temporal patterns observed here were qualitatively similar to those reported in a recent study from Holland (*15*). The regression of lung function on O_3 was repeated with these time-trend variables included in the models (Table 5). The overall FEV_1 slope on O_3 was reduced (in absolute magnitude) by about half in this model: -0.26 ml/ppb (SE = 0.07; p = 0.0003). Thus, inclusion of variables accounting for temporal trends in FEV_1 reduced but did not eliminate its relationship with O_3. The overall PEFR slope was -0.15 ml/sec/ppb (SE = 0.34; p = 0.65) with the linear time-trend variable in the regression model. Setting aside the Pine Springs data resulted in an overall PEFR slope of -1.06 ml/sec/ppb (SE = 0.33; p = 0.001). Thus, the PEFR slope on O_3 became slightly more negative after controlling for time trends.

Discussion

This study analyzed the relationship between daily variations in lung function and ambient O_3 concentrations for children attending six summer camps. When analyzed individually using a common method, FEV_1 was inversely related to O_3 concentrations at each of the camps. Pooling the data across camps, an average FEV_1 decline of 0.5 ml/ppb O_3 was observed. Pooled analysis of PEFR indicated no statistically significant overall relationship with O_3 concentrations. However, there was strong evidence for heterogeneity across camps, with four of five available studies yielding negative slopes (two of which were statistically significant) and one yielding a significant positive slope. The latter result appeared to be confounded by a strong training effect for PEFR.

While negative slopes relating FEV_1 and O_3 were seen for each camp, there was variation in the slope estimates across camps. This variation was found to be statistically significant using an F-test for heterogeneity (results not shown). Possible reasons for these differences include camp-to-camp variations in subject activity levels (resulting in different O_3 doses at a given, measured exposure level), differences in temporal patterns of O_3 concentrations (with broad peaks likely to have greater effects on lung function per ppb O_3), potentiation of the O_3 effect by other pollutants, variations across populations in inherent O_3 sensitivity and/or prior adaptation to O_3, and confounding by meteorologic factors or airborne allergens. Because of limitations in the available data, the relative roles of each of these factors in the observed variations across camps can be discussed only in qualitative terms.

There are few quantitative data on subject activity levels at the six camps. Although activity surely contributes to the random variability within and between camps, it cannot be quantified. While O_3 concentration profiles are often sharp and peaked in cities (e.g., Los Angeles), all of the camps analyzed here were located outside of major source areas and exhibited similarly shaped diurnal O_3 patterns, implying that this is unlikely to be an important differential factor. Potentiation of O_3 effects on lung function in asthmatics by acid aerosols has been demonstrated in a chamber study in which O_3 exposure was administered 1 day after a 3-hr expo-

Table 2. Slopes from regressions of afternoon forced expiratory volume in 1 sec on ozone for six camp studies[a]

Study	Slope (ml/ppb)	SE (slope)	p-value
Fairview Lake, 1984	-0.50	0.16	0.002
Fairview Lake, 1988	-1.29	0.27	0.0001
Lake Couchiching, 1983	-0.19	0.44	0.66
CARES, 1986	-0.29	0.10	0.003
San Bernardino, 1987	-0.84	0.20	0.0001
Pine Springs, 1988	-0.32	0.13	0.013

[a]For each study, data were analyzed in one model that fit subject-specific intercepts and one pooled O_3 slope.

Table 3. Slopes from regressions of afternoon peak expiratory flow rate on ozone for five camp studies[a]

Study	Slope (ml/sec/ppb)	SE (slope)	p-value
Fairview Lake, 1984	-2.00	0.80	0.013
Lake Couchiching, 1983	-2.66	1.32	0.046
CARES, 1986	-0.10	0.34	0.78
San Bernardino, 1987	-1.10	0.78	0.16
Pine Springs, 1988	+2.17	0.70	0.002

[a]For each study, data were analyzed in one model that fit subject-specific intercepts and one pooled O_3 slope. Data not available for Fairview Lake, 1988.

Table 4. Slopes of afternoon FEV_1 and PEFR on ozone for all camp studies combined[a]

Measurement	Slope	SE (slope)	p-value
FEV_1	-0.50 ml/ppb	0.07	0.0001
PEFR	+0.17 ml/sec/ppb	0.33	0.62

Abbreviations: FEV_1, forced expiratory volume in 1 sec; PEFR, peak expiratory flow rate.
[a]For each study, data were analyzed in one model that fit subject-specific intercepts and one pooled O_3 slope (no trend line).

Table 5. Slopes of afternoon FEV_1 and PEFR on ozone, with trend terms included in the models; all camp studies combined[a]

Measurement	O_3 slope	SE (slope)	p-value
FEV_1	-0.26 ml/ppb	0.07	0.0003
PEFR	-0.15 ml/sec/ppb	0.34	0.65

Abbreviations: FEV_1, forced expiratory volume in 1 sec; PEFR, peak expiratory flow rate.
[a]For each study, data were analyzed in one model that fit subject-specific intercepts, slopes on one or more trend functions, and one pooled O_3 slope.

sure to 100 μg/m^3 H_2SO_4 (*17*). Although the relevance of these data to the nonasthmatic subjects who experienced much lower acid levels at northeastern summer camps is not clear, they do demonstrate that potentiation can occur between these pollutants under laboratory conditions. Another recent chamber study investigating the interactive effects of O_3 and H_2SO_4 on lung function observed marginal evidence for interaction, but concluded that "O_3 is more important than H_2SO_4 as a cause of short-term respiratory irritant effects" (*18*: p. 431). Further, the wide range of FEV_1/O_3 slopes observed across the four northeastern camps (two in southern Ontario and two in New Jersey), which all experienced similar acid aerosol levels, suggests that differential acid exposures are not likely to be a significant factor in the inter-camp variation in response seen here.

Acute respiratory responses to O_3 vary markedly across people, for reasons that are not entirely understood (*5,19*). This physiologic variation in responsiveness is surely present in the camp studies, but it is not likely to have a large effect on the average population response estimated for each camp. Differences in average population responsiveness might occur due to differing levels of prior exposure to O_3, with associated tolerance/adaptation. However, the results of our analysis do not suggest a systematically lower response in the California studies, where elevated prior exposures may have occurred.

Data have not been reported on comparative levels of airborne allergens during the camp studies. None of the subjects analyzed here reported a history of asthma, minimizing the likelihood of confounding by airborne allergens. However, given the lack of allergen data and the potential for substantial numbers of "silent hyperresponders" (*8*), this possibility cannot be completely discounted.

It is possible that several of the factors discussed above, acting together, could underlie the variation in FEV_1 response observed across the six camps. However, given the many potential sources of camp-to-camp variability, it is both surprising and noteworthy that results are fairly consistent across the six studies. Further, a statistically significant drop in FEV_1 was observed in the pooled data set in an analysis that incorporated both the within-camp and between-camp variability. Thus, in spite of variations across camps, it can be concluded that children exposed to O_3 under natural conditions do experience acute decreases in lung function of the kind that have been demonstrated in great detail and precision in chamber studies. This confirms the real-world public health significance of those laboratory observations and raises concern that other acute respiratory effects observed in chamber studies (e.g., pulmonary inflammation) may also occur in people exposed to ambient O_3.

Quantitative comparison of the population average FEV_1 response observed here (-0.5 ml/ppb) with responses reported in chamber studies is complicated by the issues discussed above, as well as by differences in the designs and analytical methods used in the two types of studies. No in-depth analysis taking these differences into account has been reported to date. However, a brief review of chamber results suggests a reasonable degree of concordance. Setting aside nonlinearities in response, the results of the present study imply a 2.7% drop in FEV_1 for a 120 ppb increase in O_3 exposure in this population (mean FEV_1 was 2.23 l in the data set analyzed). This change is nearly identical to the 2.8% change in FEV_1 observed in 23 vigorously exercising male children exposed for 2.5 hr to 120 ppb O_3 (*1*). The change is smaller than the 7–13% declines seen in studies of adults exposed for longer periods (6.6 hr) to between 80 and 120 ppb O_3, with intermittent exercise (*2,20*). In the absence of detailed further analysis, these data offer no evidence for systematic differences in the quantitative relationships between FEV_1 and O_3 observed in camp and chamber studies.

The data analysis presented here yields population-average results within and across camps. It does not explicitly address interindividual variations in responsiveness, which, as noted earlier, are likely to be present. As pointed out by Brunekreef and colleagues (*19*), this variation is difficult to analyze in detail in acute epidemiologic studies because it is obscured by substantial amounts of random variability. As a result, attempts to determine, for example, which individuals are most responsive to O_3 using data from camp studies are problematic and generally should be avoided.

The pooled slope of FEV_1 on O_3 was reduced somewhat (in absolute magnitude) but remained statistically significant when the regression model included trend variables designed to account for training effects (*14,15*). A third-order polynomial provided a good fit to the observed time trend in FEV_1, which was characterized by a decline over the first four to five measurements, followed by a gradual increase and leveling. The pooled slope of PEFR on O_3 increased slightly after accounting for a more simple linear increase in PEFR over time. The trend variables were highly statistically significant, confirming the importance of this phenomenon. These effects on the estimated associations between lung function and O_3 suggest that confounding due to time trends may occur in some cases.

In summary, our results confirm a small, statistically significant, population-average decline in FEV_1 (but not PEFR) associated with O_3 exposures that is qualitatively similar to that reported in chamber studies. Evidence for heterogeneity in average FEV_1 response across studies was observed. Limitations of currently available data preclude definitive evaluation of the reasons for the variation in results across camps.

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